AIRS PFM Pulse Tube Cooler System-level Performance

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ABSTRACT

JPL's Atmospheric Infrared Sounder (AIRS) instrument is being built to make precision measurements of air temperature over the surface of the Earth as a function of elevation; the flight instrument is in the final stages of assembly and checkout at this time, and uses a pair of TRW pulse tube cryocoolers operating at 55 K to cool its sensitive IR focal plane.

The cryocooler development activity is a highly collaborative effort involving cooler design and fabrication at TRW, cooler characterization and qualification testing at TRW and JPL, and system-level performance characterization and instrument integration at LMIRIS. During the past few months the Engineering Model AIRS cooler has been integrated with the instrument focal plane assembly and measurements have been made on the overall thermal and operational performance of the cryosystem including vibration compatibility, ΔT from cooler to focal plane, and temperature control stability. At the same time the AIRS flight (PFM) coolers have undergone qualification and characterization testing at JPL prior to shipment to LMIRIS in January 1998, where they are now undergoing integration and system-level testing with the AIRS flight instrument.

This paper presents the measured system-level performance of the AIRS flight coolers including detailed thermal, vibration, and temperature control performance with the EM and flight instrument boundary conditions.

INTRODUCTION

The objective of the Atmospheric Infrared Sounder (AIRS) instrument is to make precision measurements of atmospheric air temperature over the surface of the Earth as a function of elevation. The AIRS instrument is scheduled to be flown on NASA's Earth Observing System PM platform in the year 2000, and is being developed under JPL contract by Lockheed Martin IR Imaging Systems (LMIRIS) of Lexington, MA. In Spring 1994, TRW of Redondo Beach, CA was awarded the contract to develop and produce the flight coolers for the AIRS instrument. After delivering the Engineering Model (EM) cooler[1] for testing and integration studies in July

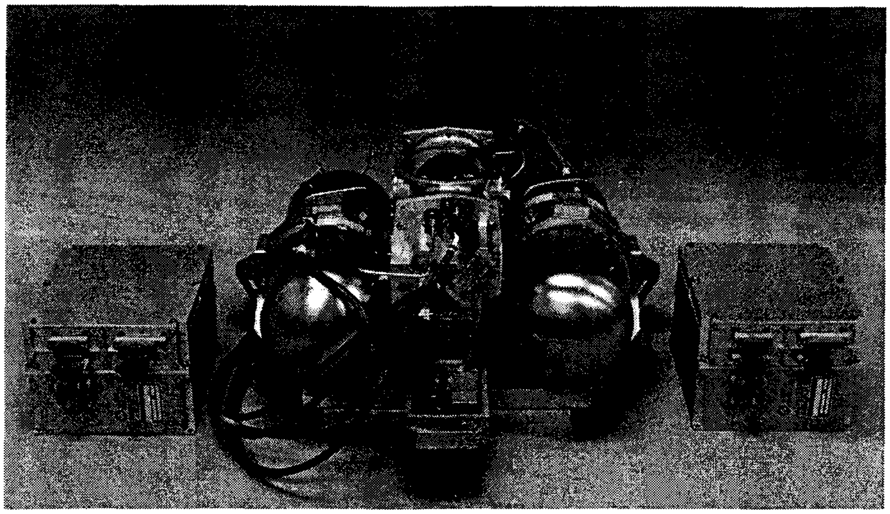

Figure 1. AIRS flight cryocoolers and drive electronics

1996, the flight (PFM) coolers, shown in Fig. 1, were delivered in November 1997.[2]

The technical foundation of the AIRS instrument is a cryogenically cooled infrared spectrometer that uses the pair of TRW 55 K cryocoolers to cool the HgCdTe focalplane to 58 K; the instrument also includes a 150K-190K two-stage cryogenic radiator to cool the optical bench assembly to 150 K. The spectrometer operates over a wavelength range from visible through 15.4 μm, and places particularly demanding requirements on the thermal, vibration, and EMI performance of the cryocoolers.

Figure 2 illustrates the overall instrument construction and highlights the key assemblies. Physically, the instrument is approximately 1.4 m x 1.0 m x 0.8 m in size, with a mass of 150 kg and an input power of 220 watts. Configurationally, the 58K IR focalplane assembly is mounted integrally with the 150K optical bench, which is in-turn shielded from the ambient portion of the instrument by the 190K thermal radiation shield and MLI blankets. The ambient portion of the instrument contains the high power dissipation components including the instrument electronics and the cryocoolers and their electronics. These high-power-dissipation components have their heat rejection interface to a set of coldplates that conduct the heat to spacecraft-mounted radiators via a system of heatpipes.

Extensive characterization of the cooler's performance has been carried out during the qualification testing and instrument integration phases at TRW, JPL and LMIRIS. These test results are described in the remainder of this paper.

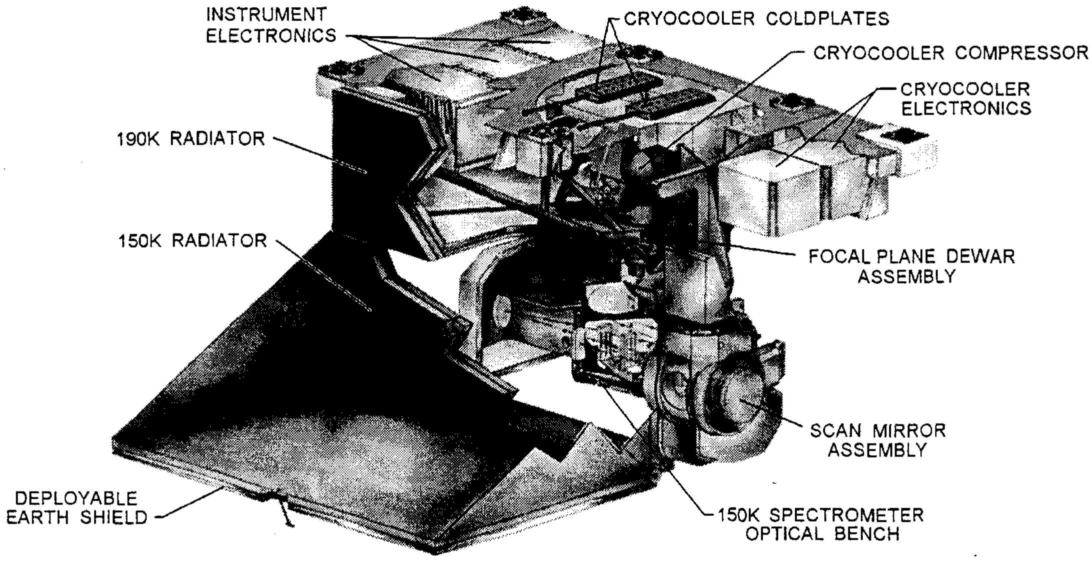

Figure 2. Operational elements of the overall AIRS instrument

AIRS Cryosystem Design and Thermal Interface Attributes

Early in the design of the AIRS instrument, key decisions of design philosophy were established that served as fundamental ground rules for the cryocooler system design. These included:

- Totally redundant cryocoolers—to avoid one cooler being a single-point failure
- No heat switches—to avoid increased complexity, cost and unreliability
- Ambient heat rejection to spacecraft-supplied cold plates operating between 10 and 25°C
- Cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics—to minimize asynchronous vibration or EMI noise pickup from the cryocooler
- Cold-end load (focal plane) mechanically mounted and aligned to the 150 K optical bench with a maximum vibration jitter on the order of 0.2 μm
- Focal plane calibration (for temperature, motion, etc.) every 2.67 sec (every Earth scan)
- Cooler input power goal of 100 watts (22 to 35 volts dc), and mass goal of 35 kg
- Cooler drive electronics fully isolated (dc-dc) from input power bus; EMI consistent with MIL-STD-461C

Based on the above fundamental ground rules, the AIRS cryosystem design, shown in Fig. 3, was developed.[3,4] This system incorporates two independent 55K cryocoolers, a primary and a non-operating backup, each connected to the 58K focal plane using a common high-conductance coldlink assembly. Ambient heat from the operating cooler is rejected to the coldplates located in the plane of the instrument/spacecraft interface. Table 1 provides a breakdown of the overall cryocooler beginning-of-life (BOL) refrigeration load measured on the AIRS Engineering Model (EM) instrument, and projections of representative end-of-life (EOL) properties. A key determiner of these BOL/EOL loads is the BOL/EOL temperature of the optical bench and pulse tube vacuum housing—assumed to be 145 K/160 K and 309 K/314 K, respectively.

Cooler Thermal Integration Considerations

To minimize thermal conduction losses between the focalplane and the cryocooler, the pulse tube coldblock needs to be located close to the focalplane. Unfortunately, in addition to providing refrigeration, the expander of a high-efficiency pulse tube refrigerator also dissipates a large amount of ambient heat — for AIRS, nearly 50% of the total compressor input power.

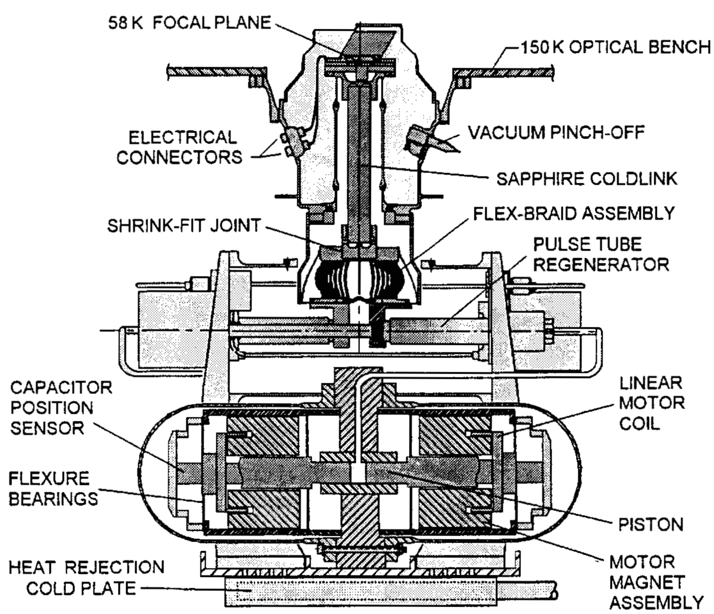

Figure 3. Schematic of AIRS cryogenic system and cooler interfaces.

Table 1. Breakdown of cryocooler loads measured on the AIRS EM instrument.

ITEM	Load (mW) BOL	EOL
FP and coldshield radiation load from OB	73	108
Focal plane electrical dissipation	193	193
Focal plane lead wire conduction	98	118
Focal plane structural support conduction	129	158
Radiation to coldlink from OB	17	24
Radiation to coldlink from vacuum housing	177	195
Off-state conduction of redundant cryocooler	486	496
Total cryocooler load	1173	1292

Thus, the expander also needs to be mounted close to the instrument heat rejection system in order to minimize its operating temperature and maximize its efficiency. With the AIRS instrument, the distance between the focal plane and the instrument heat-dissipation cold plates is approximately 45 cm (18 inches), and is spanned by a combination of the cooler-focal plane coldlink assembly and the pulse tube expander heat-rejection mounts as shown in Fig. 3.

Sapphire Coldrod/Flexlink Assembly Thermal Conductance. The sapphire coldlink assembly—designed and fabricated by LMIRIS—contains a copper-braid flexlink section at one end to accommodate the relative motion that occurs between the pulse tube and the focal plane dewar during launch and during cooldown of the instrument to cryogenic temperatures. The copper flexlink assembly bolts directly onto the two pulse tube coldblocks at one end, and at the other end attaches to the gold-plated sapphire coldrod using a molybdenum/aluminum shrink-fit interface. The total measured thermal resistance of the complete coldrod assembly from the pulse tube coldblock to the focal plane active elements is approximately 3.5 K/W as detailed in Table 2. In addition to the copper-braid section that connects the pulse tube coldblocks to the sapphire rod, the cold link assembly also contains copper braids that connect the coldblocks to one another so that the appreciable (~0.5 watt) off-state conduction of the redundant cryocooler pulse tube does not have to be conducted to the sapphire rod and back to the operating cooler.

Pulse Tube and Compressor Heat Rejection Performance. The pulse tube and compressor heatsink mounts, illustrated in Fig. 4, were designed and fabricated by TRW as part of the cooler structural support, and delivered as part of the cryocooler system. These mounts are required to conduct up to 40 watts from the operating expander to the cryocooler heat-rejection coldplate, and up to 70 watts from the operating compressor to the coldplate. The heatsink design strives to simultaneously minimize the rejection temperature of the pulse tube and compressor and the total required mass. Figure 4 describes the measured gradients between cold plate inter-

Table 2. Breakdown of predicted coldlink assembly thermal resistance; measured total on the AIRS EM instrument was 3.78 K/W.

ITEM	Resistance (K/W)
Focal plane to Sapphire rod	1.32
Conduction down Sapphire rod	0.19
Sapphire rod to moly coupling	0.19
Resistance across shrink-fit joint	0.43
Resistance across flex braid	1.20
Coldblock contact resistance	0.15
Total focal plane/pulse tube thermal resistance	3.47

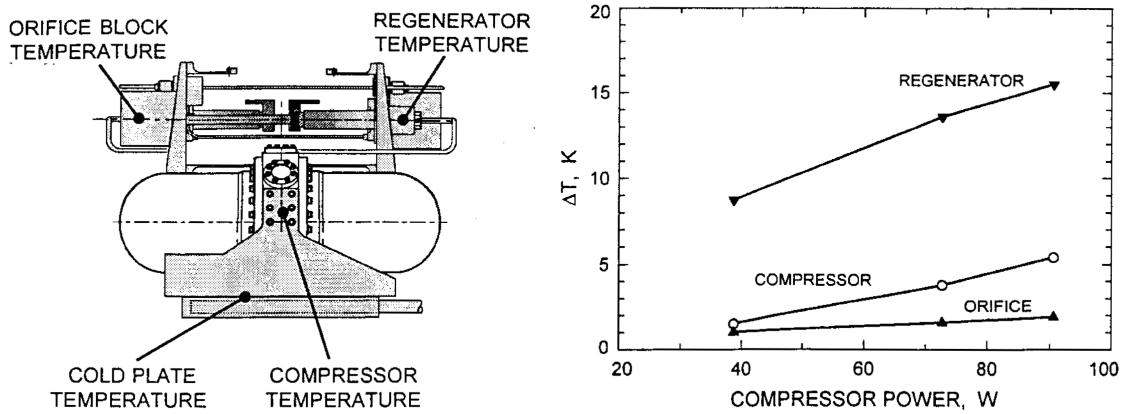

Figure 4. Temperature rise of the compressor and pulse tube regenerator and orifice block above the 25°C coldplate temperature as a function of compressor power level.

face temperature, nominally 25°C, and the operating temperatures achieved at the pulse tube regenerator, the pulse tube orifice block, and the compressor body.

Cryocooler Refrigeration Performance

One of the key attributes of the TRW AIRS pulse tube cryocoolers is their excellent thermal performance as highlighted in Figs. 5 through 7. These data are for a coldplate interface temperature of 25°C and include the effects of the significant thermal gradients detailed in Fig. 4. Note that the two flight coolers both achieve approximately 50 W/W at 55 K, but are slightly different in thermal performance, representing unit-to-unit differences. Also note that Fig. 5 is in terms of compressor input power, while Fig. 6 is in terms of total cooler system input power, including the inefficiency of the electronics. Figure 7 describes the sensitivity of the measured cooler performance to heatsink temperature. The 4-K shift in the isotherms for the 20°C change in heatsink temperature gives the 1-to-5 temperature-sensitivity ratio typical of previous TRW coolers.[5]

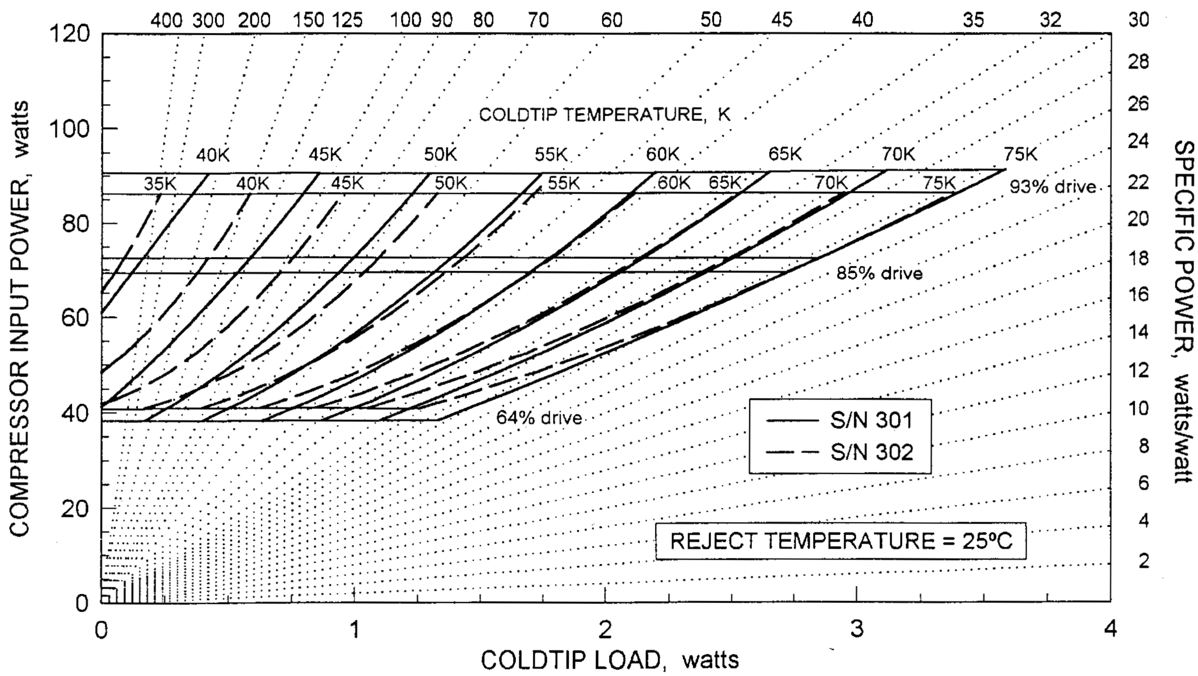

Figure 5. Measured thermal performance of the AIRS flight pulse tube coolers in terms of compressor input power with 25°C heat rejection coldplate temperature.

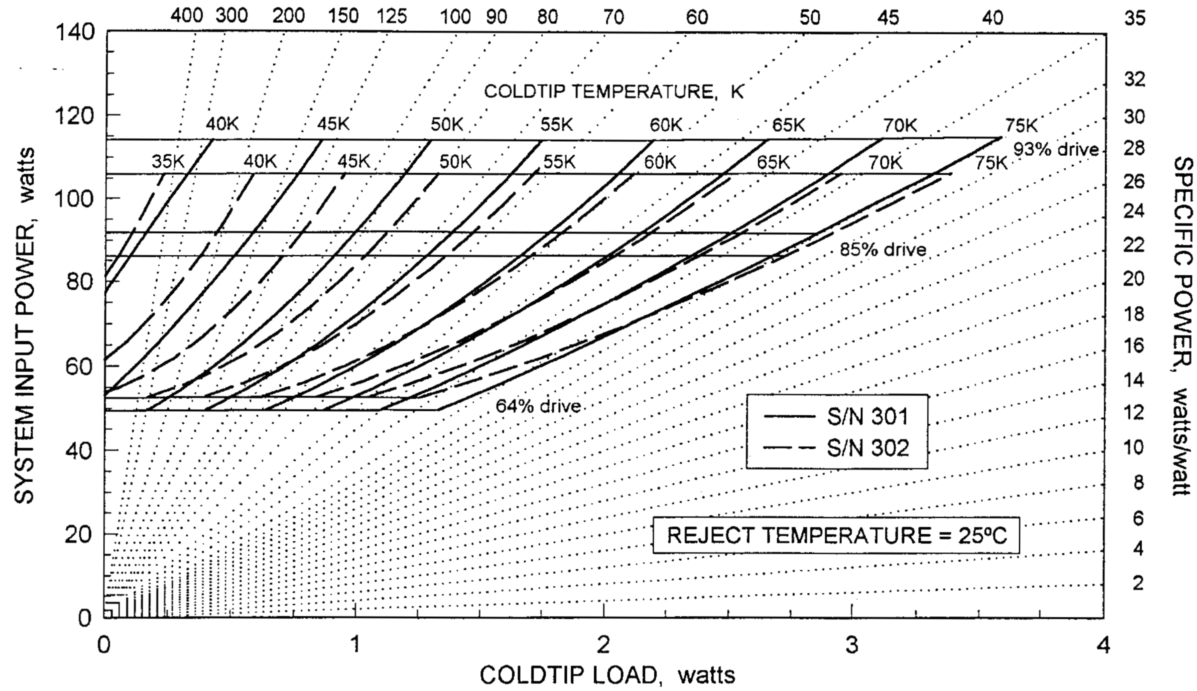

Figure 6. Measured thermal performance of the AIRS flight pulse tube coolers in terms of total cooler system input power including electronics with 25°C heat rejection coldplate temperature.

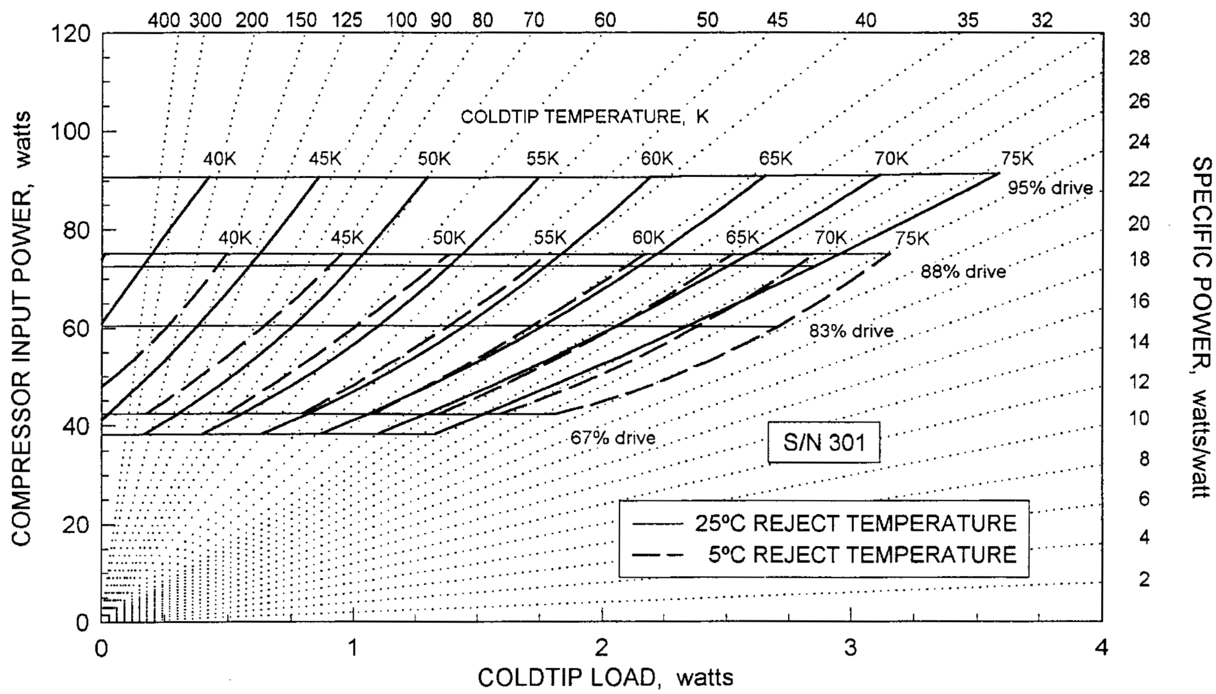

Figure 7. Measured sensitivity of the thermal performance of the AIRS flight pulse tube cryocoolers to changing heatsink temperature.

Cryocooler Electronics Performance

Included in the performance data of Fig. 6 is the efficiency performance of the AIRS cryocooler drive electronics. These electronics, shown earlier in Fig. 1, are a key part of the overall AIRS cryocooler system and play a critical role in the overall cooler performance. Figure 8 describes the details of the cooler electronics electrical efficiency as a function of load. Note that although the electronics draw on the order of 16 watts when the compressor is at zero power input, the extrapolated tare power is less than 5 watts when the compressor is running at its design load in the AIRS instrument.

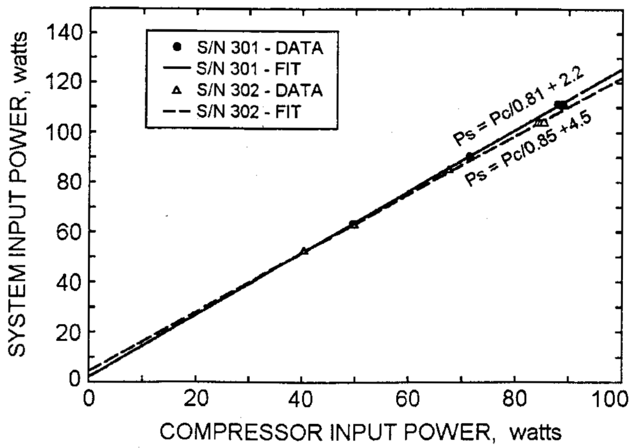

Figure 8. Relationship between total cooler system input power (including electronics) and compressor input power for compressor power levels from 0 to 100 watts.

In addition to being required to drive the compressors with high electrical efficiency, the cryocooler electronics are also required to perform a number of vital control, noise suppression, and data acquisition functions. These additional design attributes include:

- Full (dc-dc) transformer isolation from the input 28 Vdc power bus
- Built-in shorting relays to suppress cooler piston motion during launch
- Cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics—to minimize asynchronous vibration or EMI noise pickup from the cryocooler
- Very high degrees of EMI shielding, consistent with MIL-STD-461C
- Advanced feedforward vibration suppression system with accelerometer-based closed-loop nulling of the first 16 cooler vibration harmonics
- Closed-loop cooler coldblock temperature control (± 10 mK) via piston stroke control
- Built-in monitoring of cooler operational variables and performance data
- Built-in low-frequency stiction test drive waveform

Other aspects of the performance of the cryocooler electronics are described below under Electromagnetic Interference, Self Induced Vibration, and Coldblock Temperature Control.

Electromagnetic Interference

An important attribute of both the AIRS mechanical cooler and its electronics is generated EMI, particularly AC magnetic fields (Figure 9), radiated electric fields, and AC ripple current fed onto the 28 Vdc power bus. As described in detail in a companion paper,[6] the AIRS cooler

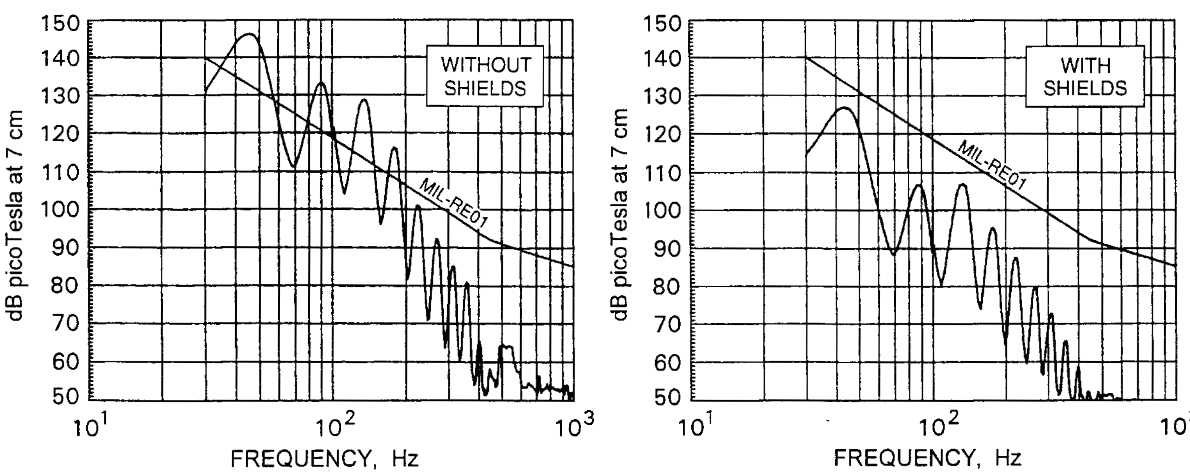

Figure 9. AC magnetic fields radiated from the AIRS mechanical cooler before and after the addition of the flight mu-metal shields — compared with the requirements of MIL-STD-461C RE01.

Table 3. Measured AIRS cryocooler AC ripple current as a function of compressor power; source impedance is S/C value of 0.25 ohms.

	S/N 301			S/N 302		
Input Power (watts)	I_{avg} (amps)	I_{p-p} (amps)	%Ripple (I_{p-p}/I_{avg})	I_{avg} (amps)	I_{p-p} (amps)	%Ripple (I_{p-p}/I_{avg})
70	2.45	5.1	207	2.44	5.8	238
90	3.16	7.3	231	3.15	8.5	270
110	4.02	9.8	244	3.94	11.7	297

design incorporates special external mu-metal magnetic shielding to suppress AC magnetic fields from the mechanical compressor drive motors, and special EMI-suppression packaging of the electronics to control radiated electric fields. With these provisions, the AIRS cooler meets all EMI requirements except in the area of AC ripple currents on the input power bus. Excessive ripple current is a particularly demanding issue for linear coolers of the Oxford type because the motor drive current varies sinusoidally at the relatively low operating frequency of the cooler — 44.625 Hz for the AIRS cooler. For AIRS, the solution involved the integration of a special power supply within the spacecraft that is able to accommodate very high cooler ripple currents, and the addition of a supplemental EMI filter within the AIRS instrument. Table 3 summarizes the input ripple current attributes of the two AIRS coolers as a function of power level.

Self Induced Vibration

Another important function of the AIRS cooler drive electronics is suppression of self induced vibration through the use of an advanced feedforward vibration suppression system with accelerometer-based closed-loop nulling of the first 16 cooler vibration harmonics. The AIRS instrument has a strong sensitivity to vibration and jitter, allowing no more that 0.2μm movement between the focal plane and the incident optical beam during any single 2.67 second scan. Figure 10 describes the measured vibration forces generated by each of the two AIRS coolers when

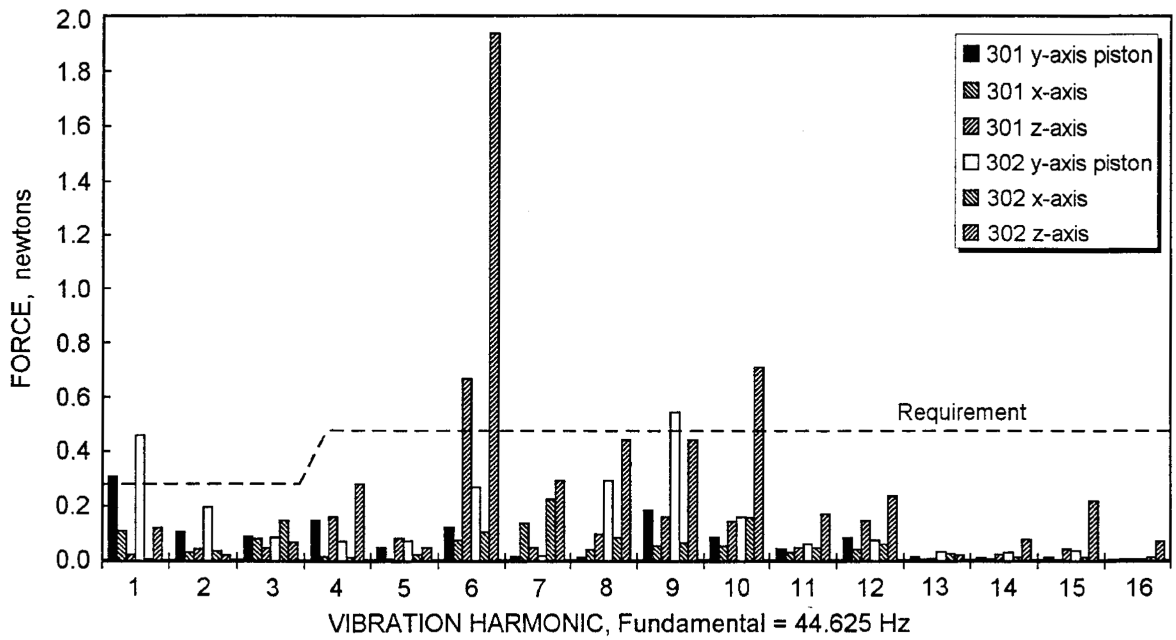

Figure 10. Vibration forces measured from the AIRS S/N 301 and S/N 302 cryocoolers during qualification acceptance testing with the active vibration suppression activated.

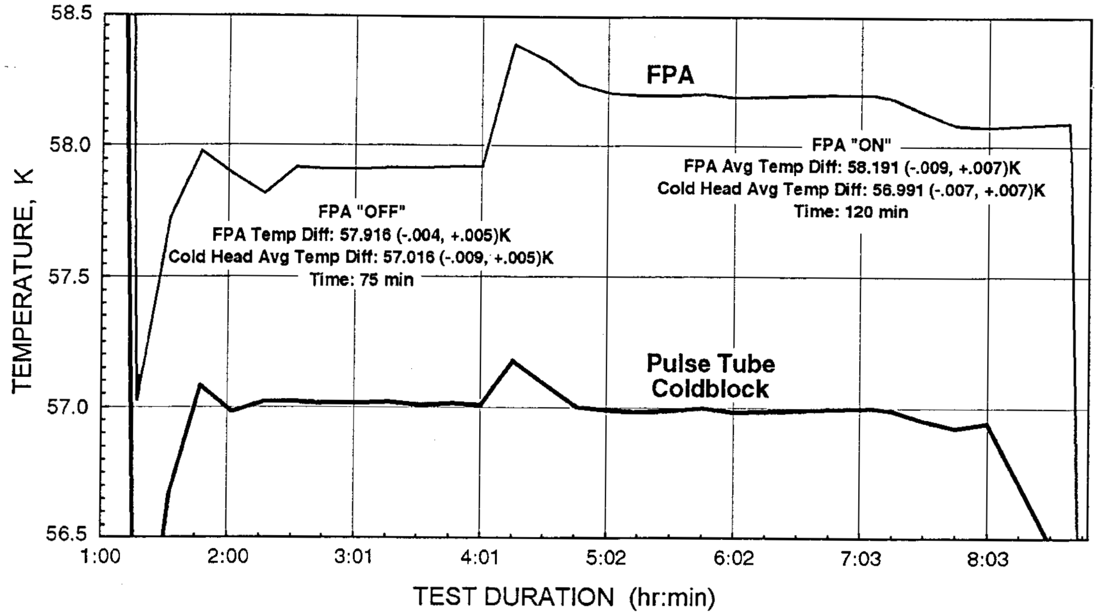

Figure 11. Focal plane and cryocooler coldblock temperature history during a system-level test involving turning the focal plane on (a ~200 mW step increase in cryocooler load) from a previous off condition.

operated individually during qualification acceptance testing. Note that the vibration is reduced to very low levels except for the 6th harmonic, which is greatly amplified by the presence of a principal structural mode in the cooler support structure around 270 Hz. Because the resonant frequencies will be different (and lower) in the final instrument configuration, the ultimate test of vibration compliance will be during system-level operation in the flight instrument. So far, cooler operation with the AIRS EM instrument has shown no measurable effects from cooler-generated vibration.

Coldblock Temperature Control

As noted above, coldblock temperature control is another demanding system-level function carried out by the AIRS cryocooler electronics. The requirement for this feature stems from a very strong sensitivity of focal plane background noise level to focal plane temperature, and a noise-rejection algorithm that requires a high level of noise stability during any individual 2.67 second scan cycle. The result is a requirement for short term focal plane temperature fluctuations no greater that 40 μK, and a corresponding cooler coldblock temperature fluctuation no greater than 10 mK. The AIRS cooler electronics performs this temperature control using digital control of compressor stroke amplitude based on temperature instrumentation on the pulse tube coldblock. Figure 11 illustrates the quality of control achieved during a severe system-level test involving turning the focal plane on (a ~200 mW step increase in cryocooler load) from a previous off condition. Note that the recovery time to reach stability is approximately one hour and the level of control is approximately $\pm$ 7 mK.

Cryocooler System Mass

As a final characterization of the AIRS pulse tube cryocooler system, Table 4 highlights the mass breakdown by element.

SUMMARY AND CONCLUSIONS

The AIRS cryocooler system development activity is a key part of the AIRS instrument development and focuses on developing and integrating the cryocoolers so as to maximize the performance of the overall instrument; it is a highly collaborative effort involving development

Table 4. Breakdown of mass of AIRS cryocooler system.

ITEM		Mass (kg)
Total cryocooler 301 (primary) weight		13.4
Compressor A	7.88	
Pulse tube expander A	0.27	
Electronics A	4.62	
Compressor-to-electronics cables	0.63	
Total cryocooler 302 (backup) weight		13.4
Pulse tube vacuum housing and heat sinks		3.6
Integrating structure/coldplate support		5.1
Compressor magnetic shields		1.5
Total cryocooler assembly		37.0

contracts with Lockheed Martin and TRW, and cryocooler characterization testing at JPL. To date, the overall cryocooler integration approach has been developed and refined, and the state-of-the-art TRW pulse tube cooler has demonstrated excellent thermal performance and light weight.

Results have been presented detailing the cryogenic loads on the cooler, the overall cryocooler thermal performance margins achieved, and thermal heatsinking considerations. Mass properties of the cryocooler system, and thermal properties of the developed coldlink assembly have also been presented.

ACKNOWLEDGMENT

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REFERENCES

1. Chan, C.K., et al., "Performance of the AIRS Pulse Tube Engineering Model Cryocooler," *Cryocoolers 9*, Plenum Publishing Corp., New York, 1997 pp. 195-202.
2. Chan, C.K., Raab, J., Colbert, R. , Carlson, C. and Orsini, R.,"Pulse Tube Coolers for NASA AIRS Flight Instrument," *Proceedings of ICEC 17*, 14-17 July 1998, Bournemouth, UK.
3. Ross, R.G., Jr. and Green K., "AIRS Cryocooler System Design and Development," *Cryocoolers 9*, Plenum Publishing Corp., New York, 1997, pp. 885-894.
4. Chan, C.K., et al., "AIRS Pulse Tube Cryocooler System," *Cryocoolers 9*, Plenum Publishing Corp., New York, 1997, pp. 895-903.
5. Ross, R.G., Jr. and Johnson, D.L., "Effect of Heat Rejection Conditions on Cryocooler Operational Stability," *Advances in Cryogenic Engineering*, Vol. 43, 1998.
6. Johnson, D.L., Collins, S.A. and Ross, R.G., Jr., "EMI Performance of the AIRS Cooler and Electronics," *Cryocoolers 10*, Plenum Publishing Corp., New York, 1999.